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Dispersion compensation in optical fibre transmission

Abstract

An optical fiber transmission system comprises an optical signal source operable to generate an optical signal at a predetermined bit rate and at a signal wavelength; an optical fiber transmission link connected at a first end to the signal source, the link having dispersion characteristics at the signal wavelength; an optical amplifier serially disposed in the link; and a signal receiver connected at the second end of the Lank; in which a grating is connected in the link, the grating being chirped by an amount providing at least partial compensation of the dispersion characteristics of the link, the compensation such as to provide a signal, at the second of the link, compatible with the sensitivity requirements of the receiver at the second end of the link.

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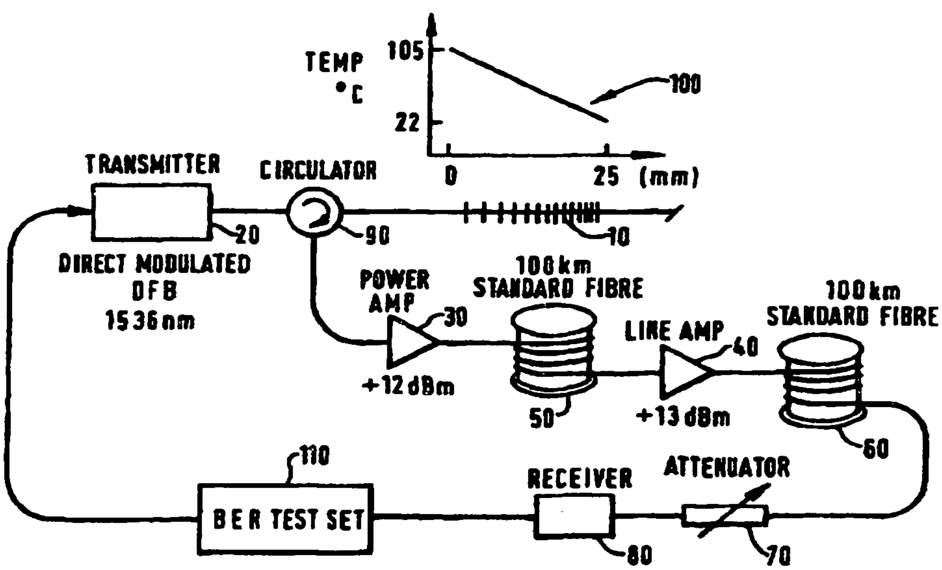

(57) Abstract

An optical fibre transmission system comprises an optical signal source operable to generate an optical signal at a predetermined bit rate and at a signal wavelength; an optical fibre transmission link connected at a first end to the signal source, the link having dispersion characteristics at the signal wavelength; an optical amplifier serially disposed in the link; and a signal receiver connected at the second end of the link; in which a grating is connected in the link, the grating being chirped by an amount providing at least partial compensation of the dispersion characteristics of the link, the compensation being such as to provide a signal, at the second end of the link, compatible with the sensitivity requirements of the receiver at the second end of the link.

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DISPERSION COMPENSATION IN OPTICAL FIBRE TRANSMISSION

This invention relates to dispersion compensation in optical fibre transmission.

Data transmission in optical fibres is generally limited by power loss and pulse dispersion. The advent of erbium-doped fibre amplifiers (EDFAs) has effectively removed the loss limitation for systems operating in the third optical communication window (around a wavelength of about 1.55μm (micrometer)), leaving pulse dispersion as a serious limitation, especially in future high-capacity multi-wavelength optical networks.

More importantly, most fibre which has already been installed for telecommunication links (ie. standard non- dispersion shifted fibre) exhibits a dispersion zero around 1.3μm and thus exhibits high (about 17ps/nm.km (picosecond per nanometre-kilometre)) dispersion around 1.55μm. Upgrading this fibre to higher bit rates involves the use of EDFAs and a shift in operating wavelength to 1.55μm where dispersion-compensation becomes a necessity.

Several techniques have been demonstrated including laser pre-chirping (reference 1 - below), mid-span spectral-inversion (phase-conjugation) (reference 2 - below), the addition of highly-dispersive compensating fibre (reference 3 - below) and chirped fibre gratings (references 4 to 7 - below). Chirped fibre gratings are of particular interest, since they are compact, low-loss and offer high negative-dispersion of arbitrary and tunable profile. In separate experiments 450fs (femtosecond) pulses have been successfully reconstructed after transmission through 245m of fibre (reference 4 - below), and gratings with dispersion equivalent to 20km and 1km of standard fibre have been fabricated (references 5 and 6 - below). Whilst more recently a grating has been employed to compensate the dispersion of 160km of standard fibre in a 10Gbits^{-1} (gigabits per second) externally modulated experiment (reference 7 - below) although no information of the grating strength was given in this case.

It is a constant aim to improve dispersion compensation techniques in optical fibre transmission systems.

This invention provides an optical fibre transmission system comprising:

an optical signal source operable to generate an optical signal at a

predetermined bit rate and at a signal wavelength:

an optical fibre transmission link connected at a first end to the signal source, the link having dispersion characteristics at the signal wavelength;

an optical amplifier serially disposed in the link; and

a signal receiver connected at the second end of the link:

in which a grating is connected in the link, the grating being chirped by an amount providing at least partial compensation of the dispersion characteristics of the link, the compensation being such as to provide a signal, at the second end of the link, compatible with the sensitivity requirements of the receiver at the second end of the link.

In preferred embodiments, the optical signal at the second end of the link has a dispersion causing a penalty in sensitivity at the receiver of less than 8.5 decibels at a bit error rate of 10^{-9} in a link longer than 200 kilometres.

Preferably the optical amplifier is operable in a saturation mode.

Preferably the chirped optical fibre grating is formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

Preferably the temperature gradient at least negates the non-linear variation of the impressed grating, thereby generating a grating having a non-linear variation in the opposite sense to the impressed grating.

It is advantageous to position the compensating grating at the input end of the link, since in this position the optical input signal is still relatively large and thus a relatively insignificant noise penalty is incurred. In addition, if the grating's (compensated) output is then routed to an optical amplifier operating in saturation, the amplifier's output power will be effectively unaltered by the presence of the compensating grating.

The skilled man will appreciate that the dispersion compensation in this context need not be complete, but simply that the non-linear response of the grating acts against the dispersion characteristics of the transmission link.

Preferably the grating is a fibre grating. Preferably the grating is a reflection fibre grating, connected using an optical circulator.

Preferably an optical amplifier is disposed between the grating an the transmission link.

Optionally, a variable attenuator may be used at the output of the transmission link.

This invention also provides an optical transmitter for use with an optical fibre transmission link, the transmitter comprising a light source capable of direct or indirect modulation and a chirped grating to provide compensation for the dispersion characteristics of the link over the range of wavelengths of the modulated light source; and an optical amplifier disposed between the grating and the transmission link, the optical amplifier being operable in a saturation mode.

This invention also provides an optical transmitter for use with an optical fibre transmission link, the transmitter comprising a light source capable of direct or indirect modulation and a chirped grating to provide compensation for the dispersion characteristics of the link over the range of wavelengths of the modulated light source, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

This invention also provides a dispersion compensating device for an optical fibre transmission link, the device comprising a chirped grating connectable at a light input end of the transmission link, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

This invention also provides an optical fibre transmission system comprising:

a light source for generating a directly or indirectly modulated optical output in dependence on input data;

an optical circulator for receiving the modulated optical output, the circulator being connected to route the modulated optical output to a reflection-type fibre grating and to route optical signals from the grating to an output port;

an optical amplifier for amplifying optical signals received from the output port of the optical circulator;

an optical fibre transmission link for propagating optical signals amplified by

the amplifier; and

an optical receiver for converting optical signals output from the transmission link into corresponding electrical data signals.

Preferably a variable attenuator is connected between the output of the transmission link and the optical receiver.

This invention also provides an optical fibre transmission system comprising:

a bit error rate test apparatus for producing test data;

a light source for generating a modulated optical output in dependence on the test data (using direct or indirect modulation);

an optical circulator for receiving the modulated optical output, the circulator being connected to route the modulated optical output to a reflection-type fibre grating and to route optical signals from the grating to an output port;

an optical amplifier for amplifying optical signals received from the output port of the optical circulator;

an optical fibre transmission link for propagating optical signals amplified by the amplifier;

a variable attenuator at the output of the transmission link; and

an optical receiver for converting optical signals output by the attenuator into corresponding electrical data signals;

the electrical data signals being compared with the test data by the bit error rate test apparatus, to detect the bit error rate of the transmission system.

This invention also provides a chirped optical fibre grating formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

This invention also provides an optical fibre transmission system comprising:

an optical fibre transmission link;

a chirped grating connected at an input end of the link to provide compensation against the dispersion characteristics of the link; and

an optical amplifier disposed between the grating and the transmission link, the optical amplifier being operable in a saturation mode.

This invention also provides an optical fibre transmission system comprising:

an optical fibre transmission link; and

a chirped grating connected at an input end of the link to provide compensation against the dispersion characteristics of the link, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

Preferably the grating is a fibre grating, and in particular a reflection fibre grating.

This invention also provides an optical fibre transmission system comprising an optical fibre transmission link; and a chirped grating connected at an input end of the link to provide compensation against the dispersion characteristics of the link.

The invention will now be described by way of example with reference to the accompanying drawings, throughout which like parts are referred to by like references, and in which:

Figure 1 is a schematic diagram of a dispersion compensating optical fibre transmission system;

Figure 2 schematically illustrates the spectrum of a DFB (distributed feedback) laser transmitter;

Figures 3a to 3c schematically illustrate the reflectivity spectra of a fibre grating as written (Figure 3a), with a temperature gradient set to add to the existing chirp (Figure 3b) and with a temperature gradient set to reverse the existing chirp (Figure 3c).

Figures 4a to 4c schematically illustrate the time delay of the gratings of Figures 3a to 3c respectively;

Figures 5a and 5b schematically illustrate sampling oscilloscope traces of an approximately 10ps, 0.318nm spectral halfwidth signal after propagation through 50km of standard fibre without compensation (Figure 5a) and with compensation (Figure 5b);

Figure 6 schematically illustrates bit error rate (BER) curves for the system of Figure 1;

Figure 7 schematically illustrates a transmission penalty at a 10^{-9} BER as a function of span length with and without dispersion compensation; and

Figures 8a to 8f schematically illustrate eye diagrams showing the different results obtained without (Figures 8a to 8c) and with (Figures 8d to 8f) dispersion compensation.

Referring now to Figure 1, in this embodiment a chirped fibre grating 10 was incorporated into a 2.5Gbits^{-1} directly-modulated system operating at 1536nm. (However, in other embodiments and in the description below, an indirectly modulated transmitter could be used instead). As a consequence of the direct modulation the output of the DFB laser transmitter 20 was chirped and exhibited a 3dB optical bandwidth of 0.1nm and a 10dB (decibel) bandwidth of 0.24nm, ie equivalent to a 10Gbit/s modulation signal.

The transmitter 20 was supplied with data from a commercial multiplexer (not shown) from a Phillips SDH (synchronous digital hierarchy) 2.5Gbits^{-1} system. The multiplexer combines 16 channels of data at 140Mbits^{-1} (megabits per second) up to a line rate of 2.5Gbits^{-1}. In the absence of data on any channel, the multiplexer generates random data. Random data was input to several of the channels whilst, on the test channel, pseudorandom data at 140Mbits^{-1} with a $2^{23}-1$ pattern length (generated by a BER test set 110) was employed. However, in a real application, it will of course be appreciated that real input data would be supplied to the transmitter instead of the pseudorandom data from the BER test set.

The transmitter 20 consisted of a directly-modulated DFB laser with wavelength centred at 1536nm and whose chirped output had a 3dB bandwidth of 0.108nm and 10dB bandwidth of 0.24nm. The spectral characteristics of the transmitter output are illustrated schematically in Figure 2. As a consequence of this chirp (and the fibre dispersion) a penalty was observed for transmission distances in standard fibre in excess of a few tens of km.

The transmitter was followed by a single-stage, 980nm-pumped erbium-doped power-amplifier 30 giving an output power of +12dBm (decibels relative to 1 milliwatt) which was transmitted through standard fibre having lengths of 100, 143 and 200km. In the latter case (as illustrated in Figure 1), a dual-stage 980nm-pumped line amplifier 40 giving an output power of +13dBm was incorporated between two series connected 100km lengths of fibre 50, 60.

The output of the link was coupled via a variable attenuator 70 to a

commercial, Phillips, receiver and demultiplexer 80, the output of which was in turn passed to the BER test set 110 for BER measurement (by comparison with the test data supplied to the transmitter 20 by the BER generator 110).

Dispersion-compensation of the link was provided by incorporating the chirped fibre grating 10 between the transmitter 20 and power amplifier 30. Since the grating 10 operates in reflection, an optical circulator 90 was included to convert it to a transmission device. The grating was connected to the circulator using so-called NTT FC/PC compatible connectors (not shown). However, to ensure successful operation, index matching liquid (not shown) was inserted in the connection to minimise reflections.

Power levels in the link are such that it is operating in the so-called linear regime, thus the dispersion compensation could in theory be performed at any location in the link. However it is advantageous to incorporate the grating in its present location (before the fibre lengths 50, 60) since the input signal to the power amplifier is still relatively large and thus a relatively insignificant noise penalty is incurred. In addition, since this amplifier 30 is then operating in saturation the output power will be effectively unaltered. Alternatively, if the dispersion compensation had been included immediately prior to the receiver a penalty would have been incurred due to its insertion loss.

The fibre grating was written using standard techniques with a frequency-doubled excimer laser in a germania-boron co-doped fibre (0.1 NA (numerical aperture), $1\mu m$ λ_{cutoff} (cutoff wavelength)). The grating was about 20mm in length with an approximately Gaussian strength profile and about 70% peak reflectivity. In its "as-written" state it had some residual chirp and a measured bandwidth of about 0.2nm. The grating was further chirped to a 3dB bandwidth of about 0.3nm by applying a linear temperature gradient. The temperature gradient could be applied to either add to or reverse the existing chirp.

Surprisingly superior performance was obtained when the temperature gradient was applied to reverse the existing chirp of the grating. This was due to the slightly non-linear characteristics of the existing chirp.

In other words, the chirped optical fibre grating is formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is

impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating, and in particular where the temperature gradient at least negates the non-linear variation of the impressed grating, thereby generating a grating having a non-linear variation in the opposite sense to the impressed grating.

Figures 3a to 3c show the grating spectral response as written (Figure 3a), with the temperature gradient set to add to (Figure 3b) and reverse (Figure 3c) the existing chirp. A slight dip is noted in Figure 3b.

Figures 4a to 4c show the time delay of the gratings, measured using an standard interferometric set up, corresponding to the respective cases illustrated in Figures 3a to 3c. (Since the measurements were performed on different instruments there is a slight mismatch in indicated wavelengths. Also, all three measurements were taken from the same end of the grating and thus in the grating of Figure 4b the grating was tested by the interferometer in the opposite direction to its direction of use in the embodiment of Figure 1).

As stated, case b (i.e. as shown in Figures 3b and 4b) did not tend to give stable link performance and thus a temperature profile 100 indicated in Figure 1 (case c, i.e. as indicated in Figures 3c and 4c) was employed. The centre wavelength of the chirped grating was also tuned to match the laser wavelength of 1536nm. Once chirped, the grating reflectivity reduced and thus the circulator-grating combination exhibited an insertion loss of 3.5dB, but owing to its location at the output of the transmitter 20 and before the amplifier 30, this had a negligible effect on the link's power-budget.

Separate measurements involving compensation for the propagation of about 10ps pulses over 50 and 100km using this grating showed structure in the compressed pulses, indicating phase-distortion of the pulses and thus non-perfect compensation of the dispersion. However, owing to the non-transform-limited data (chirped source) an improvement in system performance was nevertheless obtained.

Figure 5a shows a sampling oscilloscope trace of an approximately 10ps, 0.318nm spectral halfwidth pulse after propagation through 50km of standard fibre. The pulse can be seen to have broadened to about 281ps. After recompression with the grating, Figure 5b, the pulse width is seen to be reduced to about 39ps. However,

structure can be seen, particularly on the leading edge of the pulse which might be detrimental at higher bit rates.

Bit-error-rate (BER) curves for the system are shown in Figure 6. Data are given for back-to-back and direct transmission through 100, 143 and 200km of standard fibre. Dispersion-equalised curves, with the chirped grating included, are given for back-to-back and transmission through 100 and 200km of fibre.

In the case of direct transmission, a back-to-back sensitivity of -32.7dBm at a 10^{-9} BER is observed. At this error rate a penalty of 1.3dB was found at 100km, increasing to 3.2 and 8.5dB at 143 and 200km, respectively.

The increase in penalty with distance is shown again in Figure 7. With the grating incorporated, the back-to-back sensitivity is actually improved by 1.2dB, since the grating compresses the chirped-source pulses. The grating virtually eradicates the penalty at 100km (0.5dB) and significantly reduces the penalty at 200km to only 3dB. No floor in the error-rate curves was observed when using the grating.

The increase in penalty with distance in this case can be compared with the direct result in Figure 7, where it can be seen that the grating dispersion is equivalent (but opposite in sign) to around 60km of standard fibre. This result is in substantial agreement with the delay data illustrated in Figure 4c.

Receiver eye diagrams are shown for various points in the system in Figure 8. Although the interpretation of eye diagrams is always subjective, the skilled man will appreciate that the beneficial effect of using the grating 10 can be seen.

In summary, dispersion-compensation using a chirped fibre grating has been successfully demonstrated in a 200km standard-fibre transmission experiment using a 2.5Gbits^{-1} 1.55μm directly-modulated transmitter. The about 20mm long, 0.3nm chirped grating 10 effectively compensated for about 60km of standard fibre (i.e. fibre having a dispersion zero around 1.3μm and about 17ps/nm.km dispersion around 1.55μm), as anticipated. These results demonstrate that a non-uniformly chirped grating could provide significant improvements in current, directly modulated commercial systems.

Thus, an approximately 20mm (millimetre) long grating with substantially linear chirp, to give a 0.3nm 3dB bandwidth, substantially negates the dispersion of about 60km of standard fibre. This allowed transmission through 200km of standard

fibre with a 3dB penalty, which compares with an approximately 8.5dB penalty without the compensation.

In summary, therefore, embodiments of the invention make use of a grating is connected (in a dispersion compensating fashion e.g. using an optical circulator) in an optical fibre link, where the grating is chirped by an amount providing at least partial compensation of the dispersion characteristics of the link, to provide an output signal from the link compatible with the sensitivity requirements of the receiver at the second end of the link. In particular, in embodiments of the invention, the optical signal at the output end of the link can be made to have a dispersion causing a penalty in sensitivity at the receiver of less than 8.5 decibels at a bit error rate of 10^{-9} in a link longer than 200 kilometres.

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CLAIMS

1. An optical fibre transmission system comprising:

an optical signal source operable to generate an optical signal at a predetermined bit rate and at a signal wavelength:

an optical fibre transmission link connected at a first end to the signal source, the link having dispersion characteristics at the signal wavelength;

an optical amplifier serially disposed in the link; and

a signal receiver connected at the second end of the link;

in which a grating is connected in the link, the grating being chirped by an amount providing at least partial compensation of the dispersion characteristics of the link, the compensation being such as to provide a signal, at the second end of the link, compatible with the sensitivity requirements of the receiver at the second end of the link.

2. A system according to claim 1, in which the optical signal at the second end of the link has a dispersion causing a penalty in sensitivity at the receiver of less than 8.5 decibels at a bit error rate of 10^{-9} in a link longer than 200 kilometres.

3. A system according to claim 1 or claim 2, in which the optical amplifier is operable in a saturation mode.

4. A system according to any one of the preceding claims, in which the chirped optical fibre grating is formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

5. A system according to claim 4, in which the temperature gradient at least negates the non-linear variation of the impressed grating, thereby generating a grating having a non-linear variation in the opposite sense to the impressed grating.

6. An optical transmitter for use with an optical fibre transmission link, the

transmitter comprising a light source capable of direct or indirect modulation and a chirped grating to provide compensation for the dispersion characteristics of the link over the range of wavelengths of the modulated light source; and an optical amplifier disposed between the grating and the transmission link, the optical amplifier being operable in a saturation mode.

7. An optical transmitter for use with an optical fibre transmission link, the transmitter comprising a light source capable of direct or indirect modulation and a chirped grating to provide compensation for the dispersion characteristics of the link over the range of wavelengths of the modulated light source, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

8. A dispersion compensating device for an optical fibre transmission link, the device comprising a chirped grating connectable at a light input end of the transmission link, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

9. An optical fibre transmission system comprising:

a light source for generating a directly or indirectly modulated optical output in dependence on input data;

an optical circulator for receiving the modulated optical output, the circulator being connected to route the modulated optical output to a reflection-type fibre grating and to route optical signals from the grating to an output port;

an optical amplifier for amplifying optical signals received from the output port of the optical circulator;

an optical fibre transmission link for propagating optical signals amplified by the amplifier; and

an optical receiver for converting optical signals output from the transmission

link into corresponding electrical data signals.

10. A system according to claim 9, comprising a variable attenuator connected between the output of the transmission link and the optical receiver.

11. An optical fibre transmission system comprising:

a bit error rate test apparatus for producing test data;

a light source for generating a modulated optical output in dependence on the test data (using direct or indirect modulation);

an optical circulator for receiving the modulated optical output, the circulator being connected to route the modulated optical output to a reflection-type fibre grating and to route optical signals from the grating to an output port;

an optical amplifier for amplifying optical signals received from the output port of the optical circulator;

an optical fibre transmission link for propagating optical signals amplified by the amplifier;

a variable attenuator at the output of the transmission link; and

an optical receiver for converting optical signals output by the attenuator into corresponding electrical data signals;

the electrical data signals being compared with the test data by the bit error rate test apparatus, to detect the bit error rate of the transmission system.

12. A chirped optical fibre grating formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

13. An optical fibre transmission system comprising:

an optical fibre transmission link;

a chirped grating connected at an input end of the link to provide compensation against the dispersion characteristics of the link; and

an optical amplifier disposed between the grating and the transmission link, the

optical amplifier being operable in a saturation mode.

14. An optical fibre transmission system comprising:

an optical fibre transmission link; and

a chirped grating connected at an input end of the link to provide compensation against the dispersion characteristics of the link, the grating being formed by applying a temperature gradient to a portion of optical fibre on which a non-linear grating is impressed, the variation induced by the temperature gradient acting against the non-linear variation of the impressed grating.

15. A system according to claim 13 or claim 14 or a transmitter according to claim 6, in which the grating is a fibre grating.

16. A system or transmitter according to claim 15, in which the grating is a reflection fibre grating.

FIG. 1.

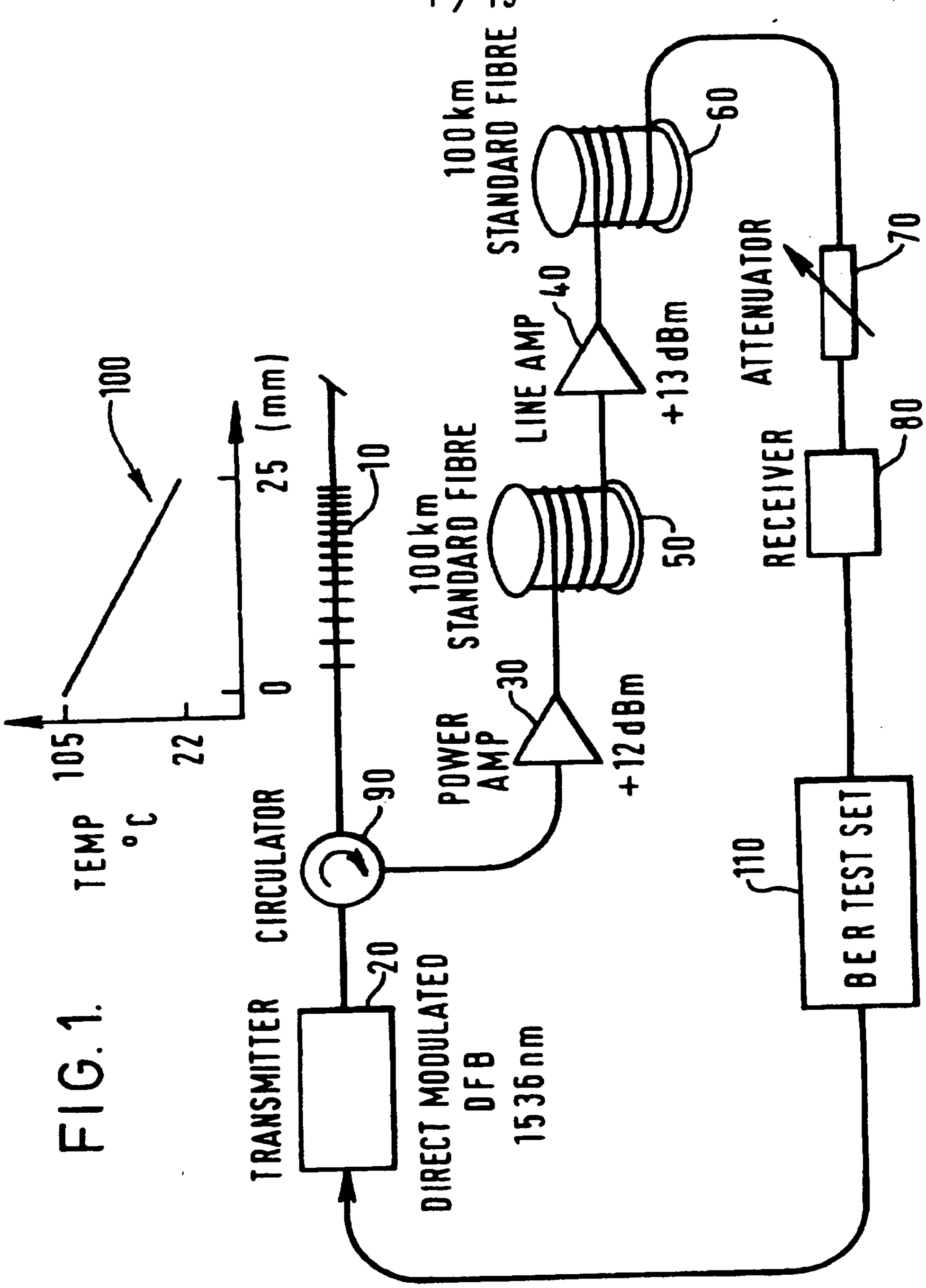
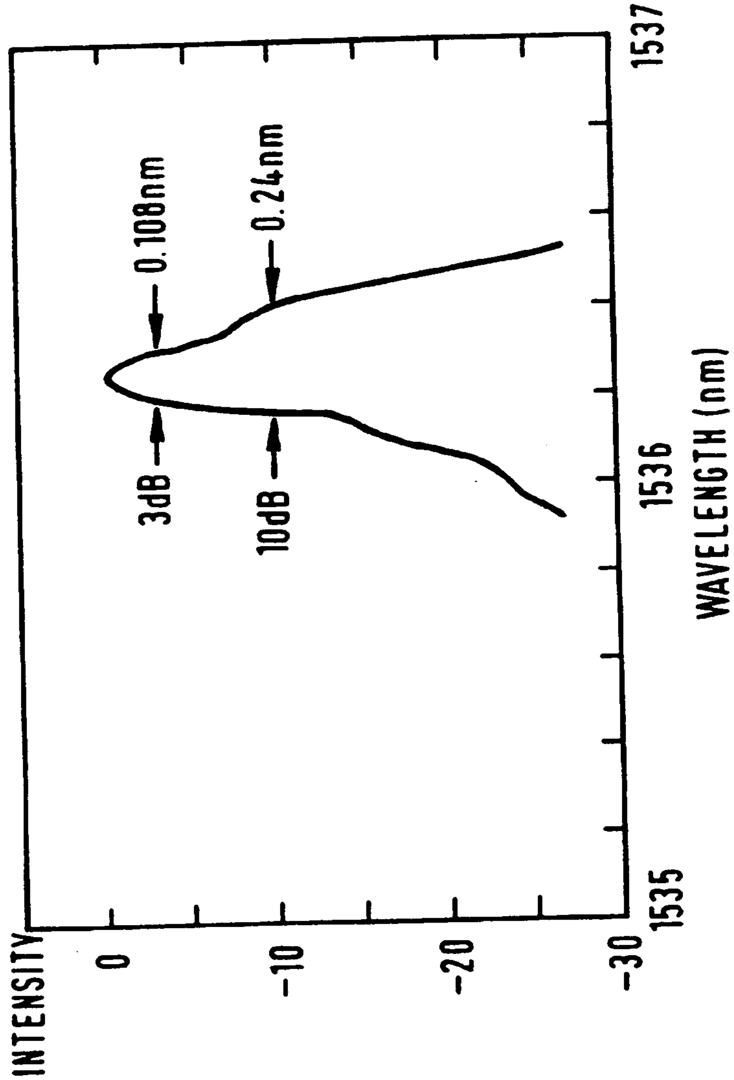

TEMP °C
105
22
0
25 (mm)
100
10
TRANSMITTER
DIRECT MODULATED
DFB
1536 nm
20
CIRCULATOR
90
POWER AMP
30
+12dBm
100km STANDARD FIBRE
50
LINE AMP
40
+13dBm
100km STANDARD FIBRE
60
ATTENUATOR
70
RECEIVER
80
BER TEST SET
110

FIG. 2.


INTENSITY
0
-10
-20
-30
1535
1536
1537
WAVELENGTH (nm)
3dB
10dB
0.108nm
0.24nm

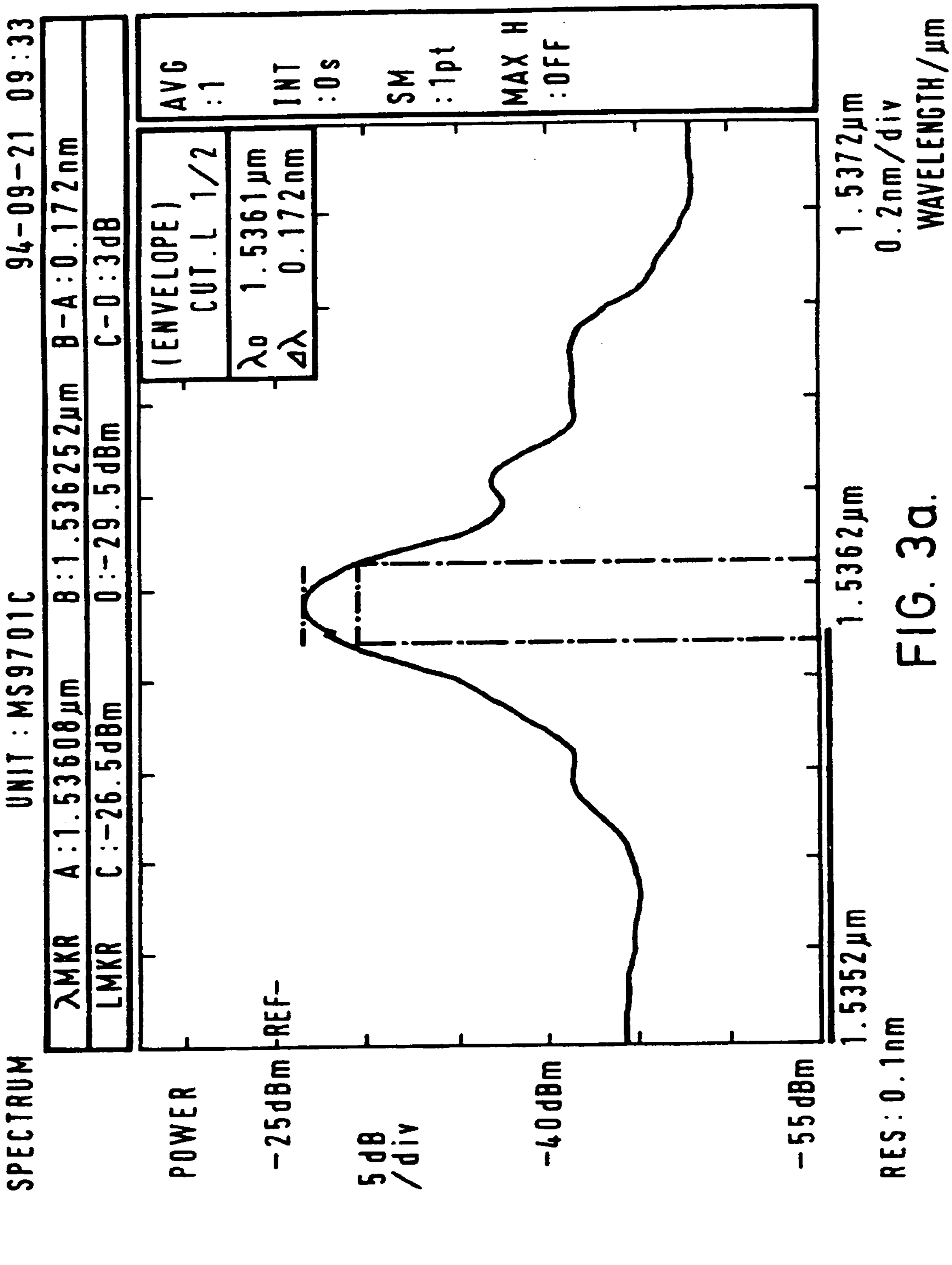

SPECTRUM
UNIT : MS9701C
94-09-21 09:33
λMKR A:1.53608μm B:1.536252μm B-A:0.172nm
LMKR C:-26.5dBm D:-29.5dBm C-D:3dB
AVG :1
INT :0s
SM :1pt
MAX H :OFF
(ENVELOPE) CUT.L 1/2
λo 1.5361μm
Δλ 0.172nm
POWER
-25dBm
-REF-
5dB /div
-40dBm
-55dBm
RES: 0.1nm
1.5352μm
1.5362μm
1.5372μm
0.2nm/div
WAVELENGTH/μm

FIG. 3a.

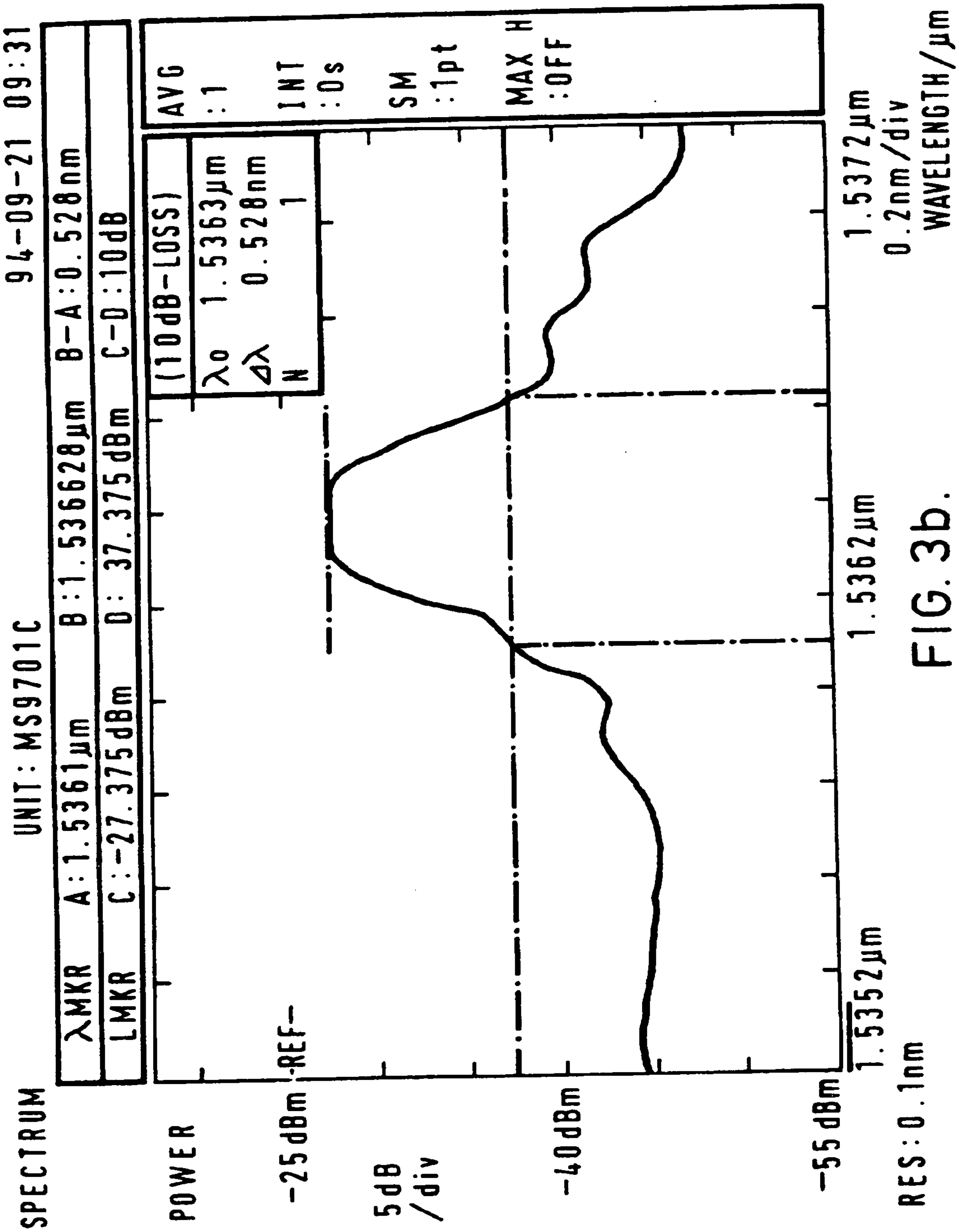

SPECTRUM
UNIT: MS9701C
94-09-21 09:31
λMKR A:1.5361µm B:1.536628µm B-A:0.528nm
LMKR C:-27.375dBm D: 37.375dBm C-D:10dB
(10dB-LOSS)
λo 1.5363µm
Δλ 0.528nm
N 1
AVG :1
INT :0s
SM :1pt
MAX H :OFF
POWER
-25dBm
-REF-
5dB /div
-40dBm
-55dBm
1.5352µm
1.5362µm
1.5372µm
0.2nm/div
WAVELENGTH/µm
RES:0.1nm

FIG. 3b.

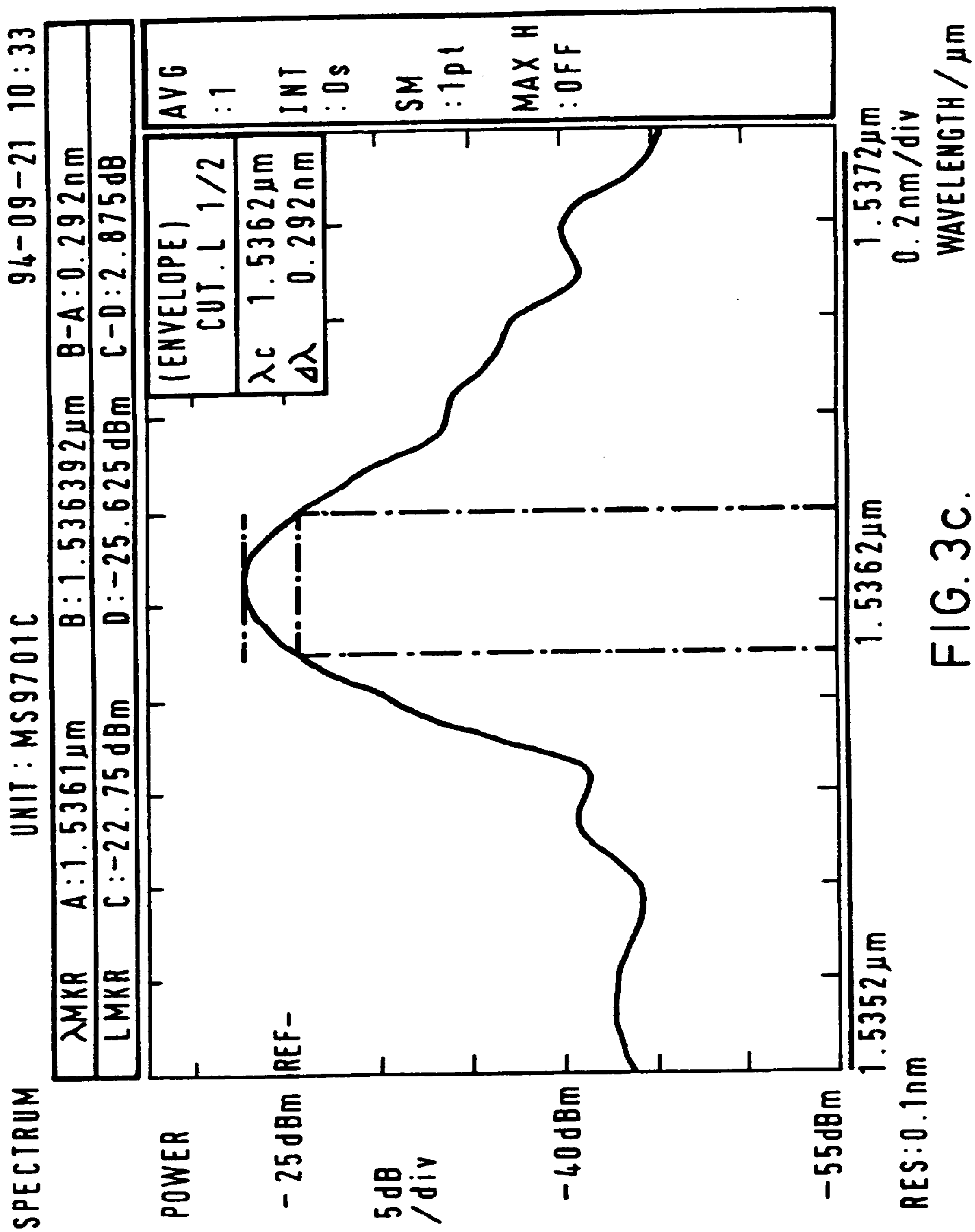

SPECTRUM
UNIT : MS9701C
94-09-21 10:33
λMKR A:1.5361μm B:1.536392μm B-A:0.292nm
LMKR C:-22.75dBm D:-25.625dBm C-D:2.875dB
AVG :1
INT :0s
SM :1pt
MAX H :OFF
(ENVELOPE) CUT.L 1/2
λc 1.5362μm
Δλ 0.292nm
POWER
-25dBm
REF-
5dB /div
-40dBm
-55dBm
RES:0.1nm
1.5352μm
1.5362μm
1.5372μm
0.2nm/div
WAVELENGTH/μm

FIG. 3c.

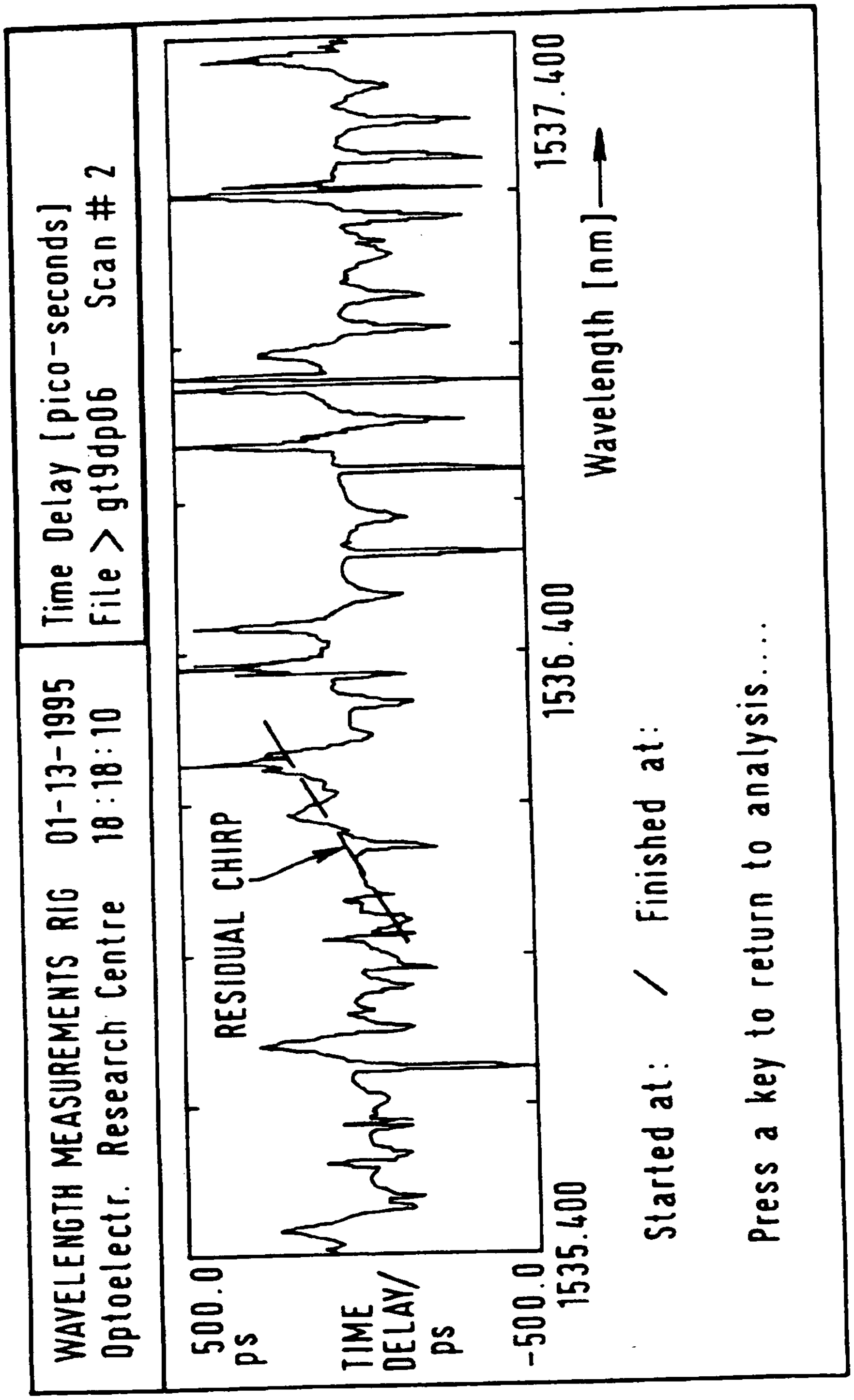

WAVELENGTH MEASUREMENTS RIG 01-13-1995
Optoelectr. Research Centre 18:18:10
Time Delay [pico-seconds]
File > gt9dp06 Scan # 2
500.0 ps
TIME DELAY/ ps
-500.0
RESIDUAL CHIRP
1535.400
1536.400
1537.400
Wavelength [nm]
Started at: / Finished at:
Press a key to return to analysis....

FIG. 4a.

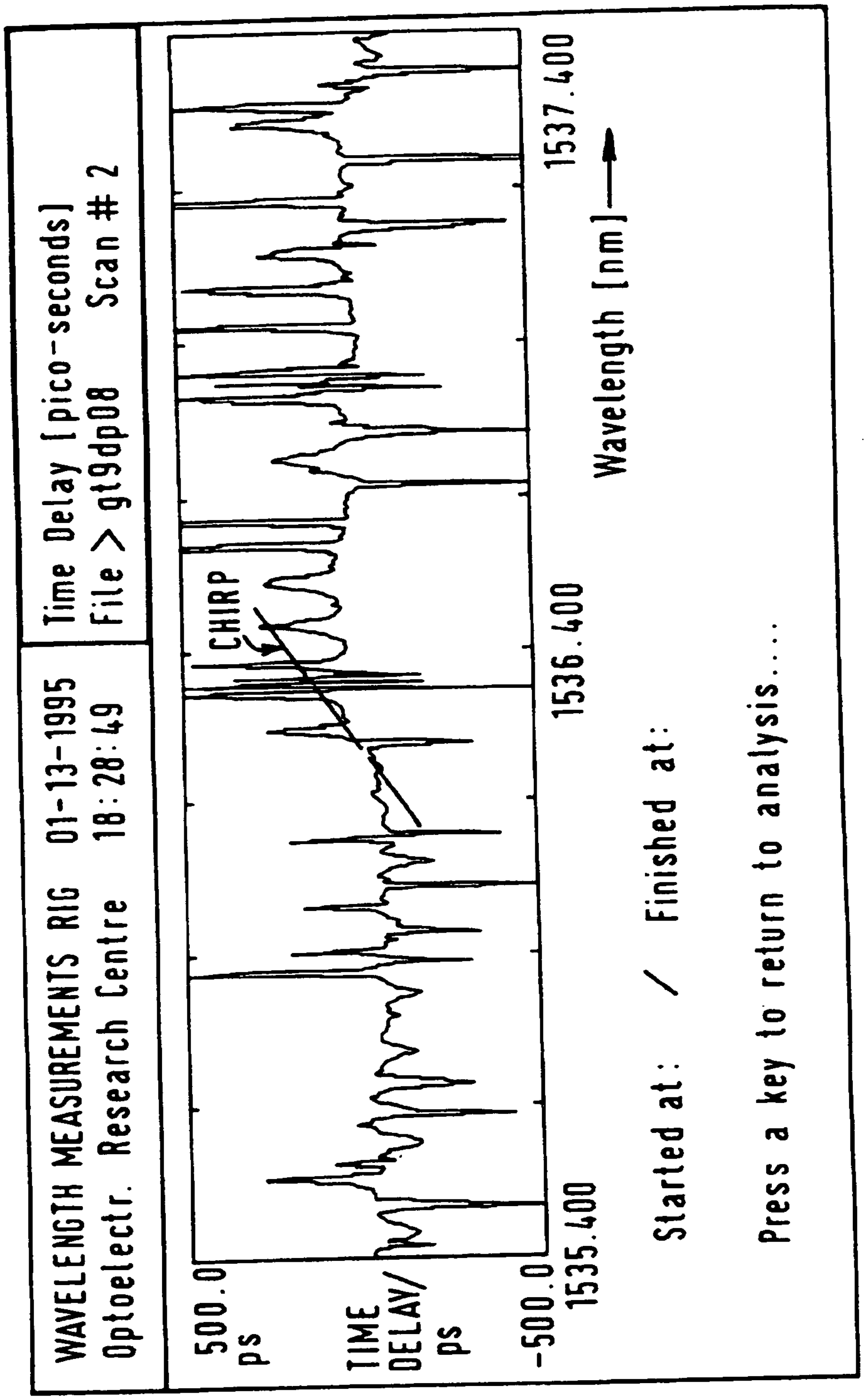

WAVELENGTH MEASUREMENTS RIG 01-13-1995
Optoelectr. Research Centre 18:28:49
Time Delay [pico-seconds]
File > gt9dp08 Scan # 2
CHIRP
500.0 ps
TIME DELAY/ ps
-500.0
1535.400
1536.400
1537.400
Wavelength [nm]
Started at: / Finished at:
Press a key to return to analysis.....

FIG. 4b.

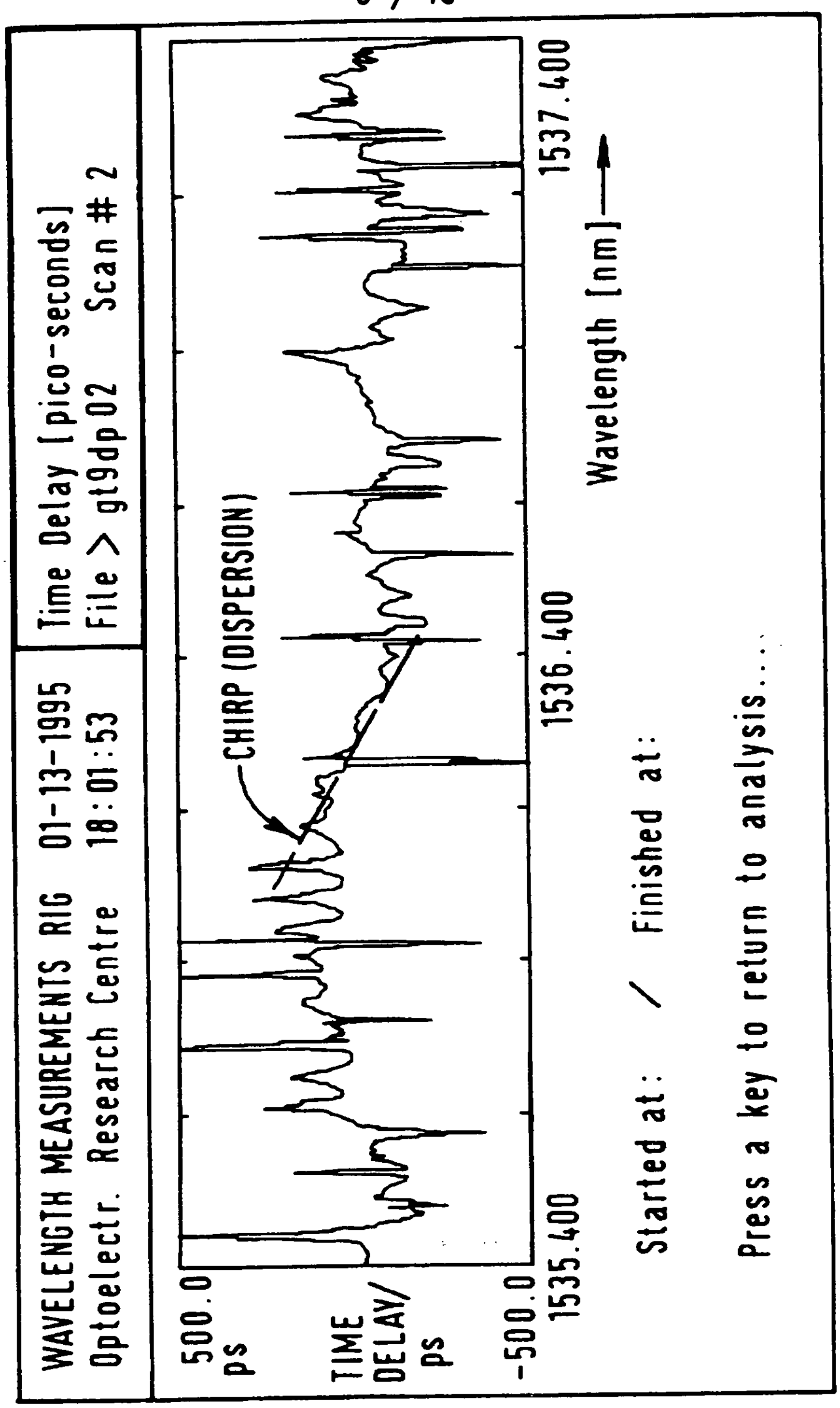
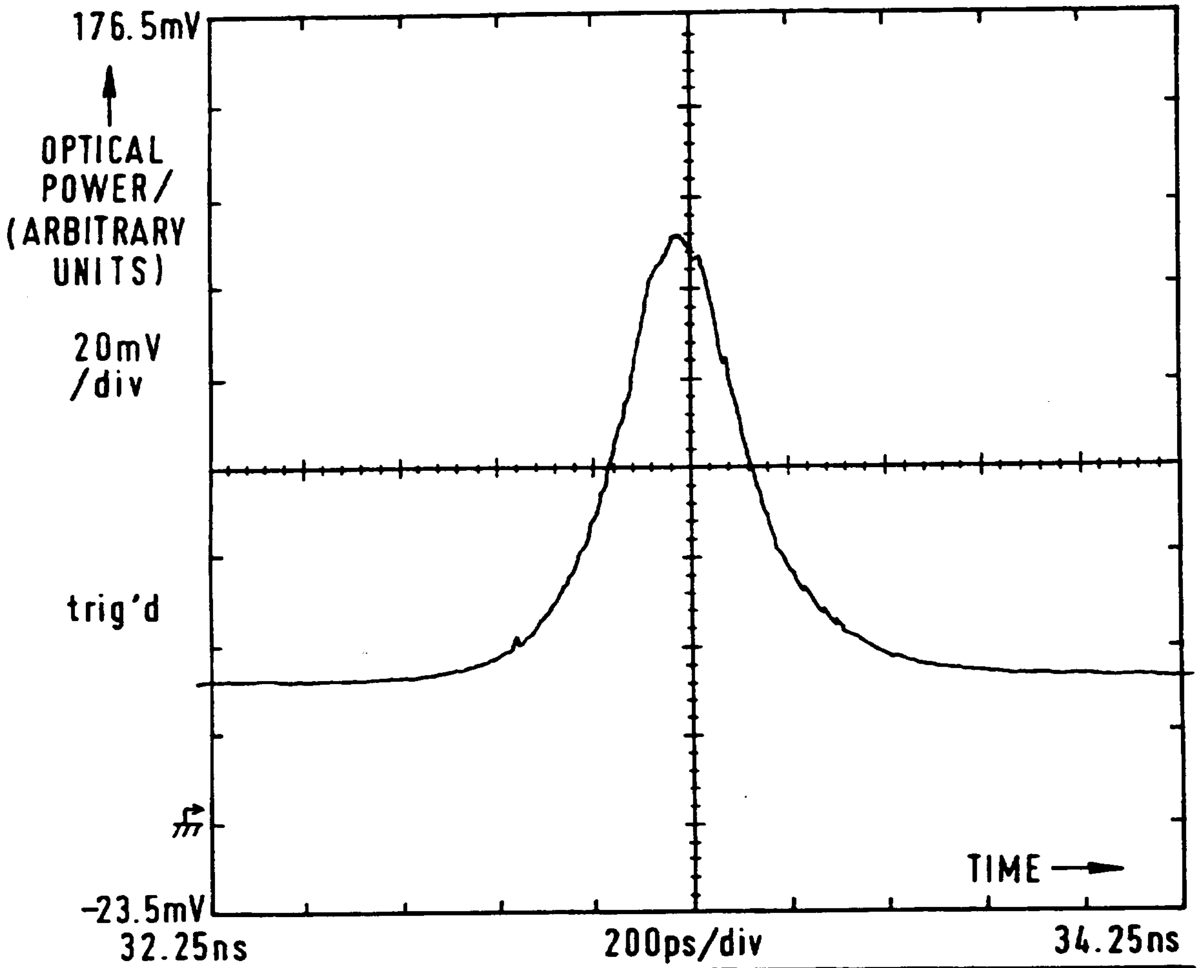
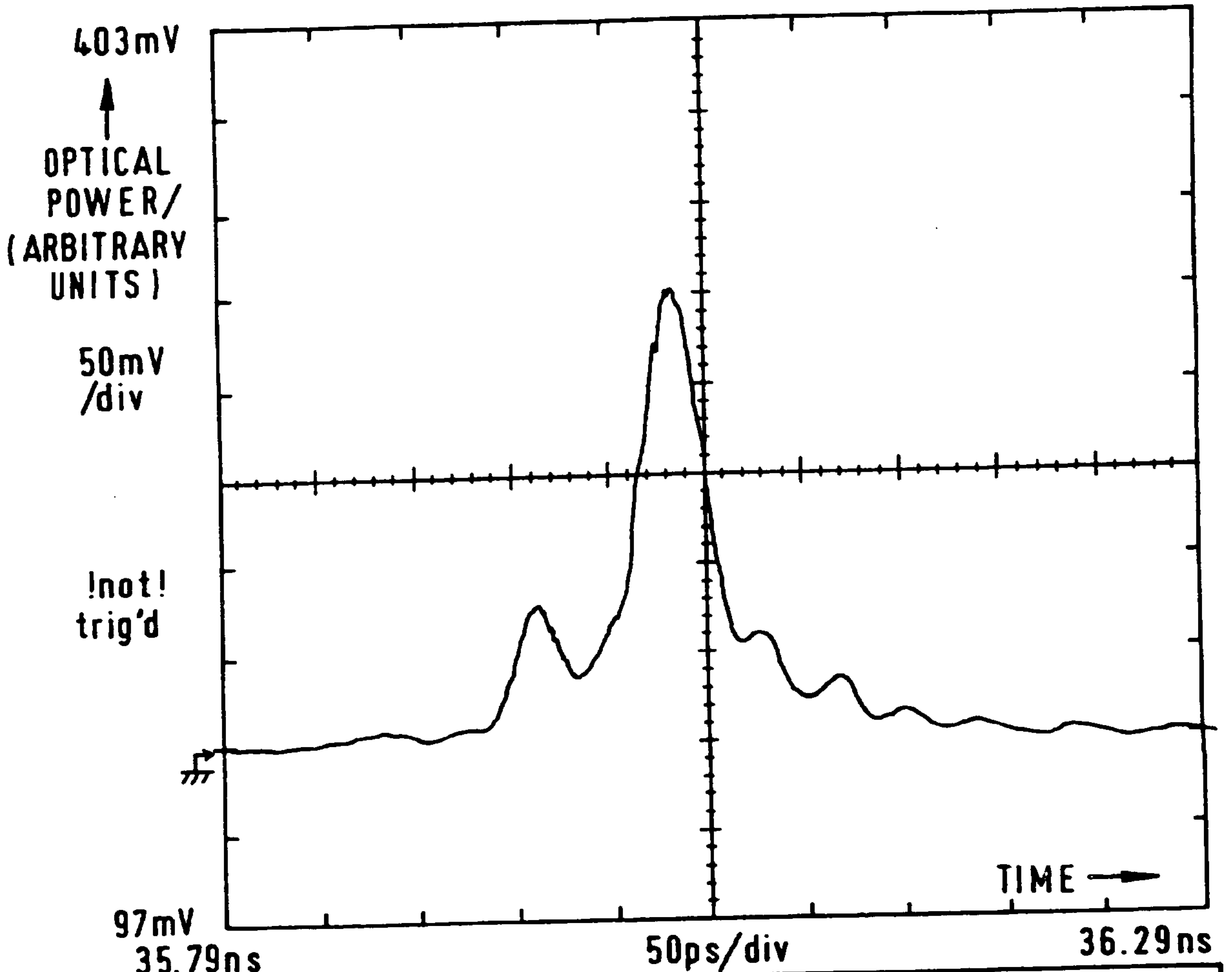

WAVELENGTH MEASUREMENTS RIG 01-13-1995
Optoelectr. Research Centre 18:01:53
Time Delay [pico-seconds]
File > gt9dp02 Scan # 2
500.0
ps
TIME
DELAY/
ps
-500.0
1535.400
1536.400
1537.400
CHIRP (DISPERSION)
Wavelength [nm]
Started at : / Finished at :
Press a key to return to analysis....

FIG. 4c.



Width 280.82 ps			Measure-ments	Vert Size: M1 20mV/div Vert Offset : M1 76.5mV	
			Compare & References	Remove/Clr Trace 1 Avg (M1) Main	Chan Sel M1

FIG. 5a.



Width 39.31 ps			Measure-ments	Vert Size: M1 50mV/div Vert Offset : M1 153mV	
			Compare & References	Remove/Clr Trace 1 Avg (M1) Main	Chan Sel M1

FIG. 5b.

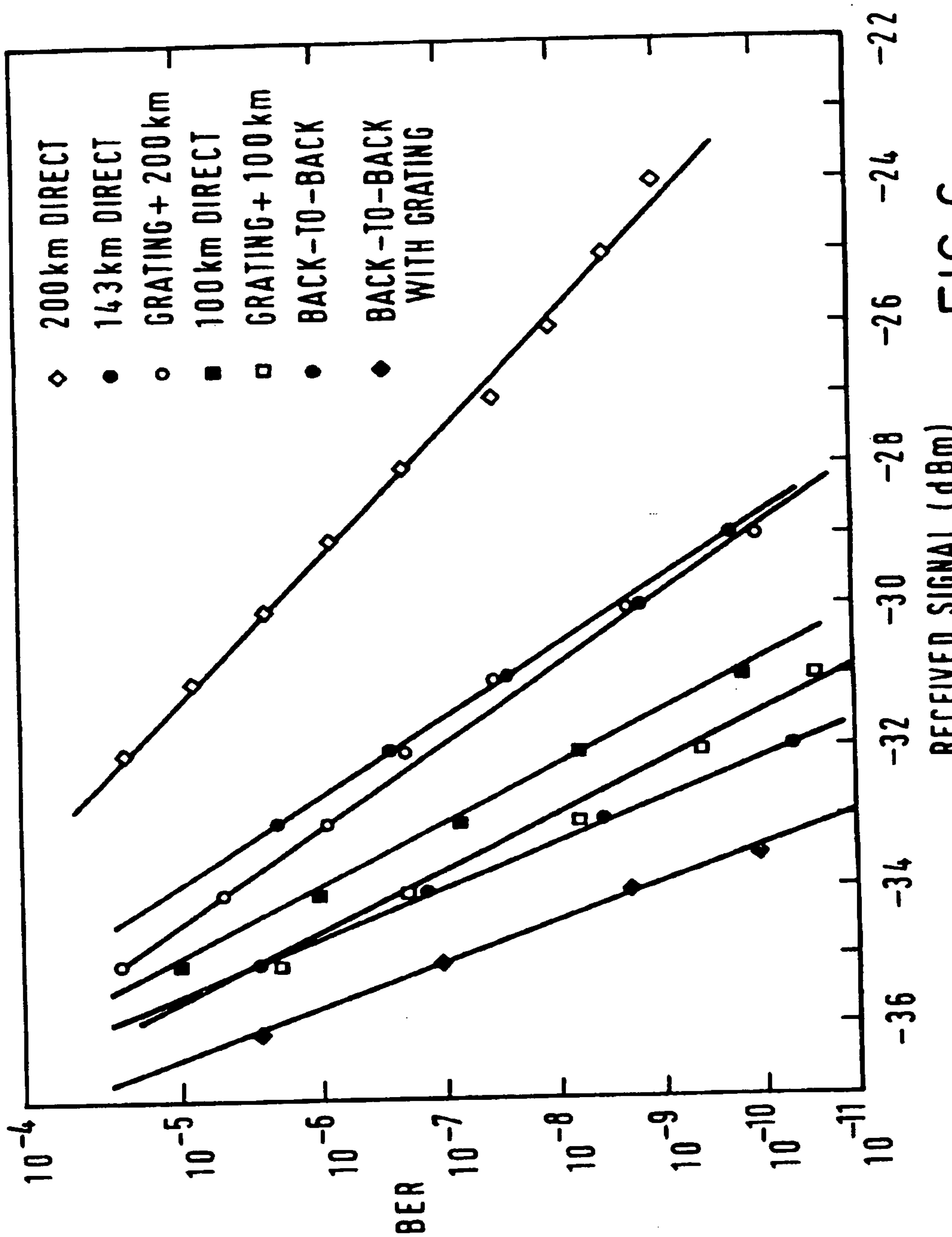
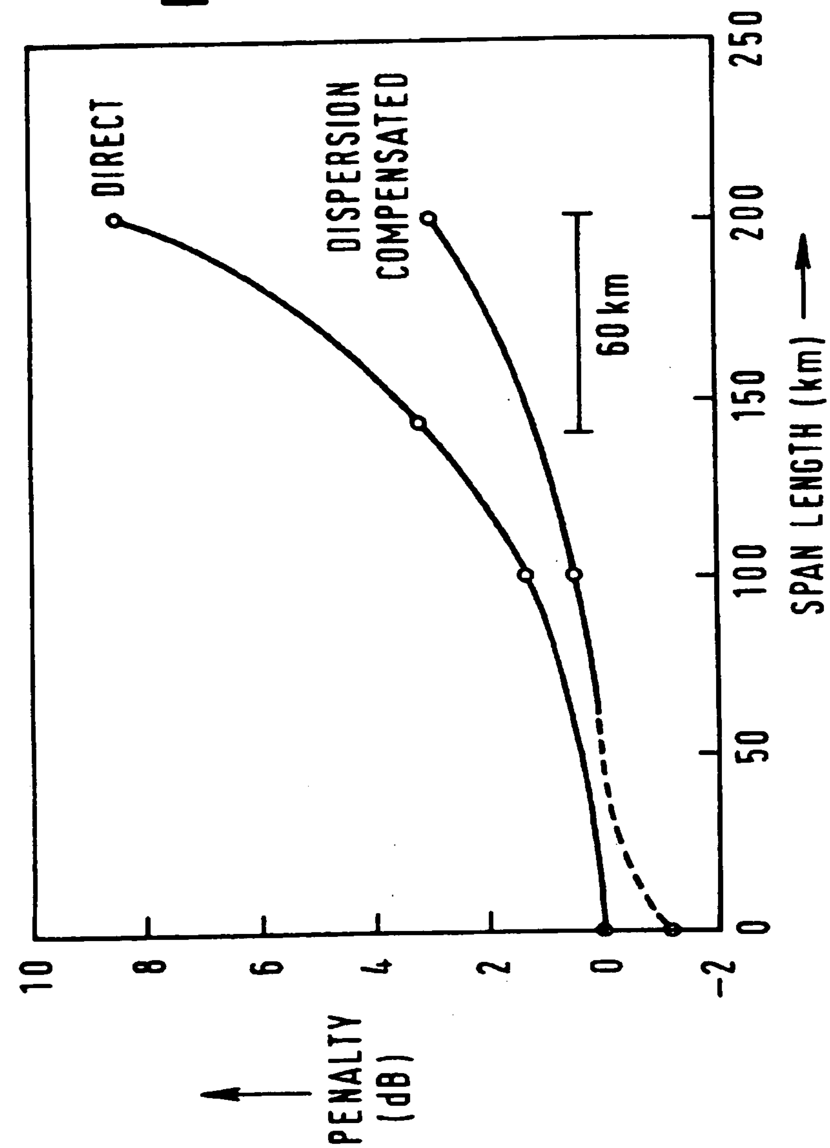

200km DIRECT
143km DIRECT
GRATING + 200km
100km DIRECT
GRATING + 100km
BACK-TO-BACK
BACK-TO-BACK WITH GRATING
BER
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
-36
-34
-32
-30
-28
-26
-24
-22
RECEIVED SIGNAL (dBm)

FIG. 6.

FIG. 7.


DIRECT
DISPERSION
COMPENSATED
60 km
PENALTY
(dB)
10
8
6
4
2
0
-2
0
50
100
150
200
250
SPAN LENGTH (km)

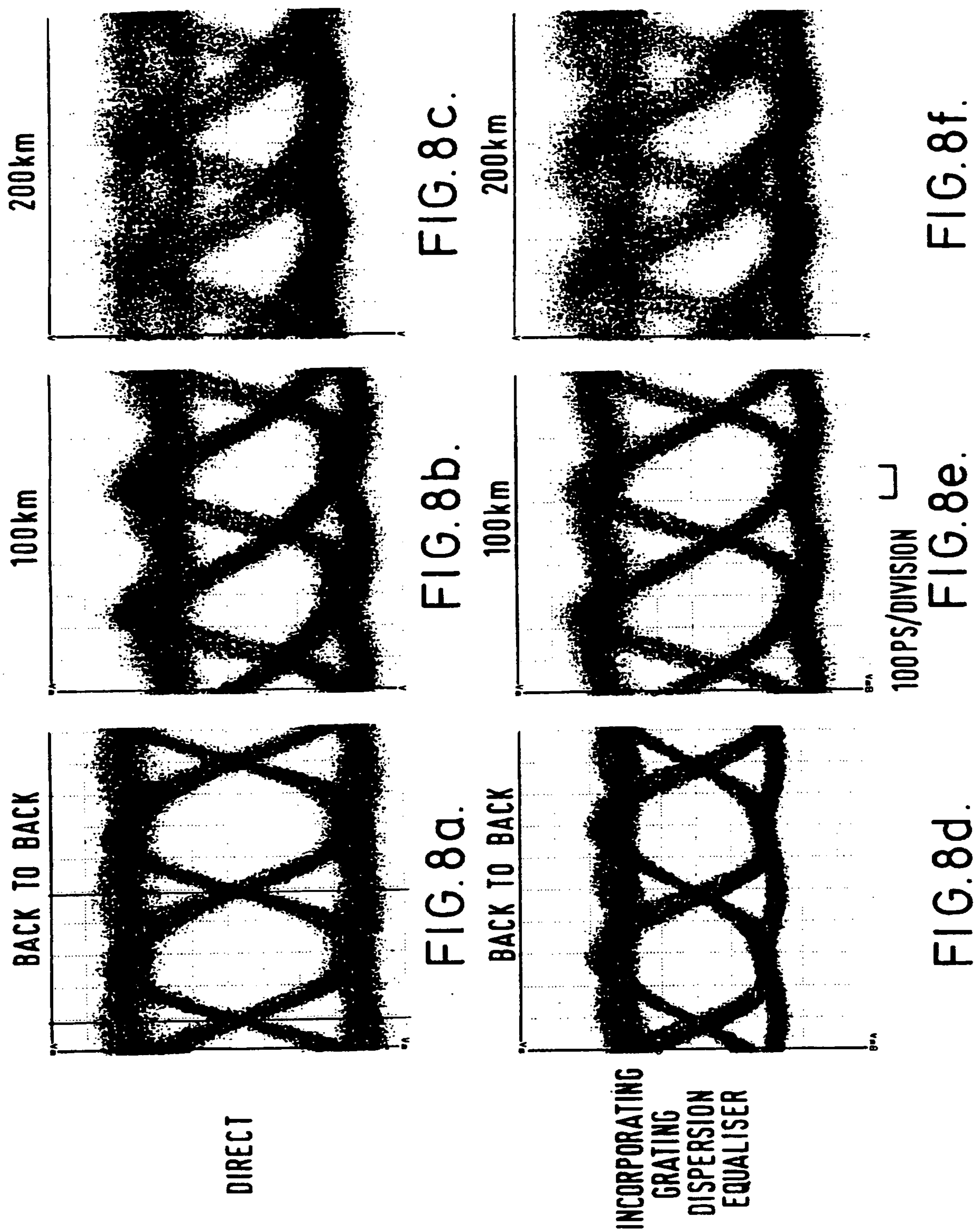


FIG.8a. FIG.8b. FIG.8c. FIG.8d. FIG.8e. FIG.8f.

INTERNATIONAL SEARCH REPORT	International Application No PCT/GB 96/00189

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B10/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	-/--	

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
16 April 1996	29.05.96
Name and mailing address of the ISA	**Authorized officer**
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Williams, M.I.

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	OPTICS LETTERS, vol. 19, no. 23, 1 December 1994, WASHINGTON US, pages 2027-2029, XP000484587 LAUZON ET AL: "Implementation and characterization of fiber Bragg gratings linearly chirped by a temperature gradient" see page 2027, left-hand column, line 1 - line 7 see page 2027, left-hand column, line 33 - line 35 see page 2027, right-hand column, line 4 - line 8 see page 2027, right-hand column, line 22 - line 26 see page 2028, left-hand column, line 23 - line 25 see page 2029, right-hand column, line 5 - line 8 see figure 3 ---	1,2,4,5, 7,8,12, 14-16
X	PROCEEDINGS OF ECOC'94. 20TH EUROPEAN CONFERENCE ON OPTICAL COMMUNICATIONS, FIRENZE, ITALY, 25-29 SEPT. 1994, pages 11-14 vol.4, XP002000636 GARTHE D ET AL: "Practical dispersion equaliser based on fibre gratings with a bitrate length product of 1.6 tb/s.km" cited in the application see page 11, line 22 - line 26 see page 12, line 12 - line 13 see figure 2	1,2,9-11
Y	---	3,6,13
Y	IEEE PHOTONICS TECHNOLOGY LETTERS, APRIL 1993, USA, vol. 5, no. 4, ISSN 1041-1135, pages 425-427, XP002000637 FARRE J ET AL: "Design of bidirectional communication systems with optical amplifiers" see abstract ---	3,6,13
A	GB,A,2 161 612 (STC) 15 January 1986 see page 1, line 82 - line 87 see page 1, line 120 - line 130 -----	1-16

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 96/00189

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB-A-2161612	15-01-86	DE-A- 3524527	16-01-86
		FR-A,B 2567655	17-01-86
		JP-C- 1804571	26-11-93
		JP-B- 5007683	29-01-93
		JP-A- 61038908	25-02-86
		US-A- 4953939	04-09-90